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A Methodology for Assessing the Impact
of Spares Positions on the Combat
Effectiveness of Small Aircraft Units

by

Theodore P. Lewis

A Dissertation Proposal in Partial
Fulfillment of the Degree Doctor of
Philosophy

Arizona State University

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Approved By

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CHAPTER I: THE PROBLEM

Introduction

> You will not find it difficult to prove that battles, campaigns, and even wars have been won or lost primarily because of logistics.
> General Eisenhower,1945 (Daniel,1947)

Logistics support has always been a key element of combat effectiveness as well as an important element in commercial transportation systems. The U.S. Air Force, like any private company, has a need to manage resources efficiently and to assess the potential capabilities of their limited resources. The Air Force is interested in developing tools and methods to assess the impact of logistics on combat capability. This research will primarily be concerned with the impact of aircraft spares support on the mission success of military combat aircraft but the basic methodology should be extendible to commercial aircraft fleets. Several Air Force organizations have an active interest in this area since they each have responsibilities in analyzing the efficiency and effectiveness of Air Force resource allocation. They include HQ USAF/LEYS, HQ AFMC WSMIS, and HQ ACC/LGSW.

Background

The following is a brief description of the logistics assessment problem. During day-to-day flight operations and training, peace-time operating stocks (POS), co-located with the unit, are used to provide spares support. When hostilities arise however, units can be deployed outside of established Air Force supply chains. In order to plan for these contingencies, additional wartime support for Air Force units is provided through the War Reserve Material (WRM) program. This program is designed to support deployed operating units and relies on prepositioning of materials based on preplanned programs and schedules (AFR 400-24, 1990). In the event of hostilities the War Reserve Material stock is additional equipment held in reserve which supplements normal peacetime operating stocks until industrial production can sustain combat requirements. It includes spares, equipment, war consumables, medical material, weapons, and other material designated as WRM by Air Force Regulation 400-24. The Mobility Readiness Spares Package (MRSP) and the In-Place Readiness Spares Package (IRSP) are a part of the War Reserve Material program for units with aircraft, vehicles, communication systems and other specified systems. A MRSP is defined as an air-transportable kit of critical spare parts that provides sustained operations during wartime or contingency operations when normal supply channels are interrupted or

fall short of demand. An IRSP performs the same function but it is meant for a unit which will stay in-place for the conflict. They are meant to sustain a unit for some specified period of time (usually 30 days) without external resupply (AFR 67-1, 1993). When resupply of these spares packages becomes available, it arrives from two sources. The first source is from repair in the field and the second source arrives via resupply channels. Items that are removed from aircraft on the flightline are sent to unit-level maintenance for repair and then returned to supply. Items broken beyond the unit's repair capability are sent to a higher level and a new part is ordered (Demmy and Hobbs, 1983)

One area of interest is the management and assessment of the recoverable spares in the Readiness Spares Packages. Recoverable spares are those parts in the aircraft which can be repaired and reused. To model the impact of these spares on combat capability, the Air Force uses a model called Dynamic Multi-Echelon Technique for Recoverable Item Control (Dyna-METRIC). Dyna-METRIC is an analytical model which runs on a mainframe computer at the Air Force Materiel Command Headquarters. Although Dyna-METRIC is a flexible tool, it has a number of limitations. This has reduced it's effectiveness in realistically predicting sortie generation capability (number of times an aircraft can fly each day) and the number of aircraft combat ready especially for units with fewer than 12 aircraft (Miyares, 1993). The model

assumes, for example, that unlimited maintenance personnel and test equipment are available, that all aircraft parts are mission-essential, and that all aircraft parts fail at the same Air Force-wide flying hour-based failure rate. Also, although the model considers the impact of component redundancy, this capability has not been effectively used (King, 1993). Due to these shortcomings, the Air Force wants a more flexible method which can address the areas where Dyna-METRIC is limited.

The original work in this area assumed that all demand processes were Poisson with a mean-to-variance ratio of one. Although subsequent work has relaxed the distribution constraint to allow the use of a negative binomial or binomial distribution, the Air Force is still using the Poisson distribution for demand calculations. Since the demand distribution has little effect on this research problem, this research will continue to use the Poisson distribution:

$$p(x) = (mT)^x e^{-mt} / x! \qquad x = 0, 1, 2, \ldots \qquad (1\text{-}1)$$

where: *m*- average annual demand

T- average time period

x- number of demands

The central theorem in this inventory model is Palm's theorem (Palm,1934). This theorem is also called the infinite channel queuing assumption (Sherbrooke, 1992).

> **Palm's Theorem:** If demand for an item is given by a Poisson process with mean *m* per unit time, and if the repair time for each failed unit is independently and identically distributed according to any distribution with mean repair time *T*, then the steady-state probability distribution for the number of units in repair has a Poisson distribution with mean *mT*. (Sherbrooke, 1992)

When the model deals with a small number of aircraft, this theorem is violated because the demand distribution and the repair cycle are no longer independent. I will give an example later which will demonstrate this problem.

The following mathematical development was adapted from Sherbrooke (1992). The number and location of all *s* spare parts can be shown in the following equation:

$$s = OH + DI - BO \qquad (1\text{-}2)$$

where OH- The number of spares on the shelf

DI- The number of items due-in from repair or resupply

BO- The number of backorders for an item

s - The stock level or inventory position

This is a balanced equation because the order quantity is assumed to be one. Any change in one variable will result in a change in another. For example, if a demand occurs, the number due-in will increase by one and, depending on the current on-hand balance, the on-hand balance will either

decrease by one or the number of backorders will increase by one.

One goal of the model is to predict the number of aircraft available and the number of sorties that can be flown during a specified time period based on an initial spares position. In order to do this the model calculates the number of expected backorders EBO(s) for each item on the aircraft based on an initial stock position. This is done using:

$$\begin{aligned} \mathrm{EBO}(s) &= \Pr[\mathrm{DI}=s+1] + 2\Pr[\mathrm{DI}=s+2] + 3\Pr[\mathrm{DI}=s+3] + \ldots \\ &= \sum_{x=s+1}^{\infty} (x - s) \Pr[\mathrm{DI} = x] \qquad (1\text{-}3) \end{aligned}$$

Another term used is pipeline. It represents the number of units of a part in repair at a location or in the resupply chain. The average pipeline is the average demand times the repair time $\mu = mT$ for the single base, full repair , no depot resupply case. As a result of Palm's Theorem, the average pipeline value becomes the mean of the Poisson distribution for calculating the expected backorders. If we allow multiple bases, limited base repair, and depot repair and resupply, the average pipeline at base j becomes:

$$u_j = m_j(r_j T_j + (1 - r_j)[O_j + \mathrm{EBO}[s_0 | m_0 T_0] / m_0]) \qquad (1\text{-}4)$$

where m_j = average annual demand at base j

T_j = average repair time at base j

μ_j = average pipeline at base j

r_j = probability of repair at base j

O_j = average order and ship time from depot to base j

subscript j = base counter

subscript O = depot counter

For most aircraft combat assessments this equation reduces to $\mu_j = (r_j T_j) m_j$ since depot repair and resupply are not available. As stated earlier, this value becomes the mean of the Poisson distribution used to calculate the expected backorders. Since aircraft availability (number of aircraft available versus the number of aircraft fielded times 100) is one of the important Air Force measures of merit, it can be calculated from the expected backorders as follows:

$$A = 100 \prod_{i=1}^{I} [1 - EBO_i(s_i) / (NZ_i)]^{Z_i} \qquad (1\text{-}5)$$

subject to - $EBO_i(s_i) \leq NZ_i$ for every i

where Z_i - number of times the same item occurs on a single aircraft

N - number of aircraft fielded

This formula implies that an aircraft is available only if there are no holes in any of the Z_i locations on the

aircraft. The constraint simply prevents the number of backorders from exceeding the number of possible aircraft holes. The number of predicted aircraft flights/flying hours is simply the number of available aircraft times the maximum flight rate which is then capped by the number of flights required (i.e. Available Aircraft * max. flight rate = number of sorties flown, capped at the daily required amount).

The following numeric example displays the mathematical problems that occur when the model attempts to assess the combat capability of a small number of aircraft. Assume our unit has only one aircraft with 2 parts A and B. The following information is known:

	part a	part b
Demand rate (dmd/flyhr)	0.05	0.03
% of base repair	100	100
repair cycle time(days)	2	3
on-hand stock	0	0

Based on the above data with a requirement to fly one aircraft, once for eight hours each day for 10 days, the model predicts the following:

	part a	part b
EBOs	0.8	0.72
Pipeline	0.8	0.72

Availability = 5.6%

This implies that you can expect to fly 0.056 sorties/day, have 0.056 available aircraft on day 10, and fly 4.48 hours for the whole 10 day period. A simulation using the same input data predicted a sortie capability of 0.47 sorties/day and an average of 38.2 flying hours during the 10 day period. The simulation model seems to give a much better picture of what might really happen because the METRIC model continues to break parts even when flying hours are not being accumulated.

Research Objective

Develop a methodology to assess the impact of spares support on combat aircraft effectiveness when deployed as a small unit with a Mobility Readiness Spares Package (MRSP).

Sub-Objectives

- Clearly define what a small unit is (ie. where do the Dyna-Metric assumptions begin to break down based on number and complexity of aircraft).

- Build a user-friendly data interface for input data manipulation.

- Document the causes of the current methods's inadequacies.

- Investigate other approaches for assessing the impact of spares support on aircraft combat effectiveness.

- Develop a methodology that addresses the analytic shortcomings of Dyna-METRIC to include redundancy, item importance, and Sortie/Fully Mission Capable (FMC) aircraft calculations.

- Validate the methodology using appropriate aircraft types and sizes and compare with actual experience.

Scope and Limitations

This research is centered around trying to find a way to more accurately predict the impact of sparing policies on the combat effectiveness of a small deployed or isolated unit. The following limits are assumed:

1) Only one aircraft type and unit will be analyzed at a time.

2) All of the aircraft are deployed or locate dat the same location so that transportation and ordering times of spares from supply are not significant.

3) Resupply from outside sources is not allowed during the analysis period.

4) The parts structure has only two levels of indenture known as line replaceable units (LRU) and shop replaceable units (SRU).

Chapter II: Literature Review

METRIC Models

The purpose of this literature review is to look at the history of Multi-Echelon, Multi-Indenture Inventory models with a particular emphasis on the development of the Dynamic Multi-Echelon Technique for Recoverable Item Control (Dyna-METRIC) model that is currently being used by the Air Force to assess weapon system wartime capabilities. The basic theorem for most of the work in this area is Palm's Theorem on queuing. This theorem is stated below:

> **Palm's Theorem:** If demand for an item is given by a Poisson process with mean m per unit time, and if the repair time for each failed unit is independently and identically distributed according to any distribution with mean repair time T, then the steady-state probability distribution for the number of units in repair has a Poisson distribution with mean mT. (Sherbrooke,1992)

This theorem is important because it states that the shape of the repair time distribution with specified mean T has no impact on the steady-state probability distribution of the number of units in repair. The steady-state distribution for the number of items in repair is going to be Poisson with mean MT (Sherbrooke,1992). The proof of Palm's Theorem is adapted from Hadley and Whitin (1963) and presented below:

PROOF:

Assume $r(p)$ is the probability that the repair time is p when the mean repair time is T. The probability of a unit completing repair at time t, having started at t_i where $t > t_i$ is shown below:

$$R(t - t_i) = \int_0^{t-t_i} r(p)\, dp \qquad (2\text{-}1)$$

If at least one demand has occurred in the interval 0 to t, then the probability that a unit is repaired by t is:

$$[R(t - t_i) / t]\, dt_i \qquad (2\text{-}2)$$

The probability that a specific demand between 0 and t is repaired by t is given by:

$$1/t\int_0^t R(t-t_i)dt_i = [1/t]\int_0^t R(p)dp \qquad (2\text{-}3)$$

Let s be the number of items available initially and n be the net inventory where the net inventory is the current stock balance minus any backorders. We want to show that as t goes to infinity, the number of items in repair has a Poisson distribution with mean mT. First, we need the probability that the net inventory at time t is n when there

have been z demands since time 0. The values of n range from s to $s - z$ where $n = s$ means all z items have been repaired and $n = s - z$ means that none of the z items have been repaired. This implies that $s - n$ items still need to be repaired at time t.

If there have been z demands, there must be $z +$ s finished repairs. The following binomial distribution represents the probability that $s - n$ repairs have yet to be completed from the z demands:

$$\mathrm{bin}(n) = \binom{z}{s-n}\left[(1/t)\int_0^t R(p)dp\right]^{z+n-s}\left[(1/t)\int\{1-R(p)\}dp\right]^{s-n} \qquad (2\text{-}4)$$

By weighting (4) by the probability of having z items demanded and summing over all $z \geq s - n$ we get the unconditional probability that the net inventory is n at time t or:

$$\begin{aligned}\Pr[\text{net inventory is n at time t}] &= \sum_{z=s-n} p(z|mT)\,\mathrm{bin}(n) \\ &= [1/(s-n)!]\left[m\int_0^t\{1-R(p)\}dp\right]^{s-n} e^{-m\int_0^t (1-R(p))dp} \qquad (2\text{-}5)\end{aligned}$$

Since we are interested in the limit of Pr[net inventory is n at time t] as $t\to\infty$, notice that:

$$\lim_{t\to\infty}\int_0^t\{1-R(p)\}dp = \int_0^\infty\{1-R(p)\}dp$$

$$= \int_0^{\infty} -p \, d\left[1 - R(p)\right]$$

$$= \int_0^{\infty} p \, (dR / dp) dp$$

$$= \int_0^{\infty} p \, r(p) dp = T \qquad (2\text{-}6)$$

Substituting this into equation (5) gives:

$$\lim_{t \to \infty} \Pr\left[\text{net inventory is n at time t}\right] = \text{poisson}\left\{s - n \middle| mT\right\} \qquad (2\text{-}7)$$

Because *s - n* is the number of items being repaired with a range of 0 to ∞, Palm's Theorem is proved.

According to Demmy and Hobbs (1983), beginning with the work of Feeney and Sherbrooke in 1966, optimization techniques for stationary, multi-echelon, multi-indenture inventory and repair systems which use *(s-1,s)* inventory policies have really progressed. Feeney and Sherbrooke (1966) describe the *(s-1,s)* inventory system where the item demands can have any compound Poisson distribution. Inventory performance in this situation is dependent solely on the spare stock level, *s*, which provides protection against stockouts. If delay times such as resupply or repair were zero, then spare stock would be unnecessary. This, however, is seldom true so optimal sparing levels are usually greater than zero. They define the *(s-1,s)* policy as a continuous review policy where a demand for *D* units results in an immediate reorder of *D* units. This keeps the

total on-hand stock plus stock on-order minus backorders equal to the spare stock level *s*. The objective is to compute the steady-state probability distribution for the number of items in resupply. First, they generalize and extend Palm's theorem to include demands that have a compound Poisson distribution. They provide a proof of this extension in an appendix to the article. In their work, they study two cases: the backorder case and the lost sales case. For this dissertation, only the backorder case is important. They provide three measures of merit:

1) Ready Rate - the probability that a unit has no backorders when reviewed at random points in time.

2) Fills - the expected number of demands that can be filled immediately from stock during a fixed period of time.

3) Units in service - the expected number of items in the resupply pipeline at any given point in time.

They also provide algorithms and FORTRAN code to calculate these performance measures in the appendices to the article.

In 1966 Sherbrooke (1966) wrote the Multi-Echelon Technique for Recoverable Item Control (METRIC) model. It originally had three purposes: 1) Optimization of base and depot stock levels subject to cost or performance constraints, 2) Redistribution of current stock levels between base and depot locations to provide optimal system performance, and 3) Assessment of system performance based on current stock levels at each location against a selected

scenario. Sherbrooke also presents several general model assumptions that he says are not exactly true but provide good approximations:

1) System Objective is to minimize the sum of backorders across all items at all bases for a weapon system.

2) The demand for each item is a logarithmic Poisson process.

3) Demand is stationary over the prediction period.

4) Decisions on where to repair an item depend only on the difficulty of repair

5) Lateral Resupply is not allowed.

6) No condemnations are considered.

7) The Depot doesn't batch items for repair.

8) Allows different priorities by base and item but not within an item.

9) Demand data across different locations can be combined.

For each of these assumptions he provides support for their acceptance. He goes on to provide some mathematical development and theory for the model and suggests methods for collecting and analyzing input data. He closes by presenting several applications. They include cost-effectiveness decisions, minimum stock levels, maximum stock levels, base reparable percentage estimation, and average base repair time estimation. Sherbrooke (1968b) also

provided a non-technical management version of this report in 1968. He (Sherbrooke,1968a) then published a shorter technical version in Operations Research. In 1971, Sherbrooke (1971) again wrote about his METRIC model. He discusses the METRIC evaluation criteria of minimizing expected base backorders subject to a budget constraint and its superiority to fill rate, the number of units supplied divided by the number demanded. But, he points out, these are still both measures of supply and only indirectly operationally relevant. He recommends using the number of aircraft Not Operational for Supply (NORS) as a more relevant measure of merit. The problem with using NORS, however, is that a model to minimize NORS aircraft is not mathematically tractable because the objective function is not a separable function of item performance measures. Also, along with some of the mathematics, he presents a case study of the F111 aircraft. He uses this case study to demonstrate the effectiveness of the METRIC model. First, he computes an F111 package of spares using the METRIC model subject to two budget constraints of 3.49 and 3.89 million dollars. Next, he evaluates these packages using NORS aircraft as the measure of merit. Then experimenting with other stocking policies, he tried to obtain spares packages that gave better NORS values with the same budget constraints. After many trials, the best improvement over the METRIC model performance in terms of NORS aircraft was less than 1 percent. He considers this reassuring but warns

that the results are empirical and based on only one test sample. Also, additional policy trials may still be able to reduce the NORS value although he does not think much improvement will occur. This is the first in a series of models that will eventually form the basis of the Air Force aircraft recoverable spares assessment and requirements computations.

In 1973, Muckstadt wrote the MOD-METRIC model. This extended the original work of Sherbrooke by allowing multi-indentured items to be considered. Muckstadt (1976) continued his work and in 1976 wrote the Consolidated Support Model (CSM). It was an extension of the MOD-METRIC model that allowed a three echelon system to be analyzed versus MOD-METRIC's two echelons. This model also added an additional constraint or assumption. Every line replaceable unit (LRU) fixed at the intermediate repair facility can have no more than one broken shop replaceable unit (SRU). The model allowed users to look at requirements for not only assemblies or line replaceable units (LRU) but also for the subassemblies or shop replaceable units (SRU). His article goes on to describe the mathematical development of this extension and provides an algorithm for determining stock levels. He then uses this algorithm to compute stock levels for jet engines at base and depot level. Muckstadt also points out that although he has included only two levels of indenture, the analysis method is easily extended to additional levels of indenture.

Finally, in 1980 Hillestad and Carrillo (1980) made a significant breakthrough by finding a method to model nonstationary demand and service rates. This was important because assuming stationary demand patterns when transitioning from peace time to war time was not considered appropriate. This particular work is very mathematical and theoretical. In it they were able to produce many time dependent measures of system performance and derive transient results for nonstationary distribution periods. These results laid the groundwork for the Dynamic Multi-Echelon Technique for Recoverable Item Control (Dyna-METRIC) model. Hillestad (1982) then wrote the Dyna-METRIC manual which provides a less rigorous mathematical description of the model along with a description of its capabilities and basic assumptions. Deming and Hobbs (1983) provide a brief but functional comparison of Dyna-METRIC and MOD-METRIC showing that they have similar theoretical foundations but Dyna-METRIC has several features that MOD-METRIC does not. It can consider three supply echelons versus only two in MOD-METRIC. Dyna-METRIC can also estimate ready rates, sortie rates, and other measures of aircraft readiness. The only drawback for this expanded capability is Dyna-METRIC's inability to optimize system-wide spares levels which MOD-METRIC can do. Dyna-METRIC can only optimize at the base level.

According to Pyles (1984), Dyna-METRIC was developed to provide five new pieces of logistics information for decision makers. They include:

1) Operational performance measures.

2) Effects of wartime dynamics.

3) Effects of repair capacity and priority repair.

4) Problem detection and diagnosis.

5) Assessments or requirements.

He also gives examples of the typical Air Force performance measures for this time period which include:

1) Resource Counts (ex. shelf stock and War Reserve Material (WRM))

2) Process delay times (ex. repair time and order and ship time)

3) Peace time customer satisfaction proxies (ex. percent requisitions filled, Not Mission Capable (NMC) aircraft, and cannibalization rates)

Then he points out that although each of these measures provides some measure of overall support for U.S. Air Force systems, there is no integrated method to assess overall support or even the relative importance of individual components. This, he claims, is where Dyna-METRIC can provide support. It ties the resource counts and process delay times to the important operational concerns of number of sorties flown and number of fully mission capable (FMC) aircraft available and can do all of this under dynamic wartime scenarios. The report also provides an extended

example of how to use the model for a single F16 squadron deploying to a single base. Pyles also provides a list of Model limitations, a description of each limitation and its impact on modeling. The limitations are:

1) Repair procedures and productivity are unconstrained and stationary.

2) Forecast sortie rates do not reflect flight - line resources and the daily employment plan.

3) Component failure rates vary only with the user defined flying program.

4) Aircraft at each base are basically the same.

5) Repair decisions and actions happen after component testing.

6) Item failure rates are not adjusted at based on previous sorties completed.

7) The repair processes are the same at every echelon's repair facility.

Gage and Ogan (1983) give some additional limitations that are important. For example, the actual sorties flown by the model can never exceed the requested sorties. Also, the Not-Mission Capable due to Supply (NMCS) figure given by the model is not necessarily equivalent to the number of grounded aircraft. It simply means the aircraft is not able to accomplish all of it's required missions. Put simply, the model does not consider Partially Mission Capable (PMC) aircraft. The model also still carries the assumptions that the repair and demand processes are independent, the depot

is an unconstrained source of supply, and the intermediate repair facility distributes parts based on base cumulative flying hours. Gage and Ogan see Dyna-METRIC as a valuable management tool but warn that it's not the final truth. Because of the model assumptions and limitations, they recommend continual review of the outputs for validity and reasonableness.

The next step in the evolution of the multi-echelon, multi-indenture modeling effort came in the form of VARI-METRIC (Sherbrooke, 1986). Since that time, several investigators have developed exact solutions for this problem but they require more restrictive assumptions and substantially more computer time. Slay (1980) developed VARI-METRIC and Graves improved upon it. Graves (1985) showed that in 11% of the cases, METRIC computed stock levels varied by at least one unit from the optimal while VARI-METRIC only differed in 1% of the cases. This improvement is achieved by taking into account not only the mean pipeline value as the previous models did but also looking at the variance of the pipeline quantities. Sherbrooke (1986) shows that in the case of multi-indenture, multi-echelon systems, VARI-METRIC gives estimates of backorder quantities that are very close to those calculated by simulation models. Thus, he believes that VARI-METRIC is an improvement over MOD-METRIC and Logistic Managements Institute's Aircraft Availability Model. To back up this

claim, he presents several case study comparisons of the VARI-METRIC and MOD-METRIC models.

Dyna-METRIC version 3.04 became the standard aircraft unit assessment system in 1988. It fell under the umbrella of the Weapon System Management Information System (WSMIS) of the Air Force Logistics Command (AFLC) now known as the Air Force Material Command (Isaacson et. al., 1988).

This model represented a full scale implementation of the model discussed in Hillstad and Carrillo (1980), Hillstad (1982), and Pyles (1984). Version 4 is the current version being used in the Air Force for weapon system assessment (Isaacson et. al., 1988). It was developed to assess worldwide logistics support of aircraft spares including the depot-theater interactions. This allows someone to assess movement of spares from one theater to another or to assess the impact of base/theater/depot repair processes, stock levels, transportations processes, cannibalization policies, and wartime plans interactions on the military's combat capability. It also allows the user to view how spares support for subcomponents may impact combat capability by showing the impact of these parts in the repair process at each echelon. Isaacson, Boren, Tsai, and Pyles (1988) give a detailed description of the differences between version 3.04 and version 4. As mentioned earlier, one assumption of the METRIC-type models is unconstrained repair facilities. In 1989 Tsai (1989) wrote Dynamic Simulation of Constrained Repair (Dyna-SCORE)

to try to study the impact of maintenance policies on weapon system availabilities. The model's outputs include summaries of job processing times, component pipeline contents, backorder quantities, weapon system availabilities, and equipment utilizations. The problem with Dyna-SCORE is that it is a single-echelon model that focuses on only one repair shop and assumes that all other shops and echelons have no impact on aircraft availability except to fill requisitions or create demands for the modeled shop (Tsai, 1989). Dyna-METRIC version 5 (Isaacson and Boren, 1988) was an attempt to extend the model to consider constraining or controlling repair processes and uncertainties. It attempted to do this by replacing the pipeline component calculations based on Palm's Theorem with a Monte Carlo simulation. Its biggest limitation was that in an attempt to model constrained repair it does not model part's subcomponents. This implies that a part will never be delayed in a repair facility while it waits for parts (Isaacson and Boren, 1988). Version 6 released in 1993 is an enhancement of version 5. It was an attempt to place back in the model the version 4 features that had been left out of version 5. It still uses Monte Carlo simulation for determining pipeline quantities and attempts to fix the version 4 problem of computing pipeline demands based on scheduled flying hours rather than actual flying hours. Its most significant limitations include an inability to compute spares requirements and very long run times (Isaacson and

Boren, 1993). Two other versions of the model should also be mentioned. Dyna-METRIC Microcomputer Analysis System (DMAS) is a microcomputer version of the Dyna-METRIC version 4 model used by the Air Force. It has restricted capabilities and is primarily intended for base-level users who are doing unit level requirements and assessment calculations (DRC, 1993a). Major Command Dyna-METRIC microcomputer Analysis system (MAJCOM-DMAS) is a windows-based microcomputer version of Dyna-METRIC version 4 but it is intended for more sophisticated scenarios. It provides access to a much larger selection of the version 4 capabilities. This version has all the features of DMAS but also allows multi-unit, multi-echelon, theater-level assessments (DRC, 1993b).

Verification and Validation

Model verification and validation are important aspects of any model building research. Many definitions of these terms exist in the literature. Pritsker (1986) defines verification as "The process of establishing that the computer program executes as intended." Khoshnevis (1994) defines it as a "computer implementation of the model that is error-free," and he points out it is not concerned with establishing whether the model is reasonable. Pegden (1990) agrees that it is checking the model to see that it performs as expected and intended. Law and Kelton (1991) see verification as a debugging process.

Validation is defined by Pegden (1990) as the process of raising the user's confidence to an acceptable level such that he is willing to use inferences drawn from the model about the real system. Shannon (1975) agrees with this definition. Pritsker (1986) calls validation the process of achieving a desired accuracy between the model and the real system. Khoshnevis (1994) defines it as the process which establishes that the model and the input data represent the important aspects of the modeled system. Gross and Harris (1985) and Lee, Moore, and Taylor (1990) view validation as a combination of the verification and validation processes while Shannon (1975) credits Fishman and Kiviat(1967) with breaking the model evaluation process into three steps:

1) Verification - that the model runs as the modeler intended,

2) Validation - that there is agreement in the behavior of the model and the real system,

3) Problem Analysis - that the model user is capable of drawing significant inferences from the model results.

The question of verification and validation boils down to answering the question, does the model represent reality?. Specht (1968) warns that the model is just an "analog of reality" and may not represent every aspect of reality. He stresses that the important thing is that the model outputs answer our questions in an appropriate and valid manner. He states that because we do not have complete knowledge the best we can hope to do is answer the following questions:

1) Can the model describe clearly and correctly the known facts and circumstances?

2) When the input parameters are varies, are the results consistent and reasonable?

3) How does the model handle special cases where we have some indication of the outcome?

4) Can it assign causes to known effects (Specht,1968). Shannon (1975) states that it is impossible to prove that any model is the true or correct model of a system but adds that this is seldom important since we are primarily concerned with validating the insights gained from the model. He stresses that these insights provide the model

utility not the model structure accuracy. Specht (1968) agrees. He says we should not be upset that a model does not look like the real thing or that it does not represent all of reality. He adds that several models for the same reality may be valid depending on the questions asked and the decisions affected. Pegden (1990) clarifies this discussion by saying that verification is where the modeler gains confidence in the model and validation is where the modeler transfers that confidence to others.

As stated above, validation is the process of convincing the decision maker or model user that the model accurately reflects the real system for the user's decision making or analysis purposes. Pritsker (1986), Gross and Harris(1985) and Lee, Moore, and Taylor (1990) all agree that validation is the more difficult of the two evaluation tasks. The ultimate goal of any model is to aid the decision maker, therefore, the modeler would like to test the correctness and relevance of the results. Since this is not always possible, says Specht (1968), the best we can sometimes hope for is to be honest. Further, claims Quade (1968), no matter how hard the analyst strives to maintain a scientific inquiry or to follow scientific methods, military systems analysis is not an exact science. Although it may appear rational, analytical, and objective, do not be fooled. Human judgment is used in the analysis for:

1) creating the analysis design,
2) determining the relevant factors,

3) determining the interactions to model and what those to leave out,

4) choosing the alternatives to consider,

5) selecting input data,

6) analyzing and interpreting results.

Thus, Quade cautions, judgment and intuition are infallible and, as such, caution is advised for both the modeler and the decision maker to avoid biasing the model results (Quade, 1968). Specht gives a similar warning:

This fact - that judgment and intuition and guesswork are embedded in a model - should be remembered when we examine the results that come, with high precision, from a model.(Specht, 1968)

Verification is usually done by using a manual check of the calculations claims Pritsker (1986). Gross and Harris (1985) recommend a similar method. Pegden (1990) says the best support for verification comes from proper program design, plus clarity, style, and ease of understanding. He also recommends a four step approach to verification that includes establishing a skeptical frame of mind, using outside skeptics, conducting model and experimental walk-throughs, and performing test runs. As part of this process, Law and Kelton (1991), Khoshnevis (1994) and Pegden (1990) all recommend computer animation as a valuable verification tool, if it is available. Khoshnevis (1994) states that models usually fail to operate correctly as a result of coding errors or logic errors. Coding errors, he

says, are usually the easier of the two types to find because they stop the program's execution process and are usually located by the compiler's error checking system. Logic errors, on the other hand, are much more difficult to find and correct. Both Khoshnevis (1994) and Pegden (1990) provide lists of the most common error types. These lists include such things as data errors, entity flow problems or deadlocks, problems with units of measurement, and overwriting model variables. They both also suggest techniques to avoid these common errors. Law and Kelton (1991) provide 8 different techniques for verification that include modular code construction and testing, debugging using a program trace function, animation, and structured walk-throughs.

Specht (1968) and Law and Kelton (1991) each present equivalent three step approaches to model validation. They recommend:

1) testing the face validity of the model - These tests determine whether a model seems reasonable to experts familiar with the system under study.

2) testing the model assumptions - This involves testing quantitatively the assumptions that were made in the model early in development.

3) testing the reasonableness of the input-output transformation - This involves testing whether or not the model produces results similar to the real or proposed system.

Steps two and three can use a number of statistical techniques and methods for completing these steps. These techniques include statistical tests of means and variances, regression, analysis of variance, autocorrelation, and non-parametric tests. Shannon (1975) warns, however, that each of these test procedures comes with its own set of assumptions that must be considered. Hillier and Lieberman (1986), Pritsker (1986), Gross and Harris (1985) and Pegden (1990) all agree that using standard statistical tests is the way to go if data exists for comparison. If data does not exist, Hillier and Lieberman (1986) recommend using face value testing but also suggested field testing to collect data, if possible, and using experts in the field to perform sensitivity analysis on the model under a variety of different scenarios. They point out, however, that field testing is frequently costly and time-consuming and therefore, often impractical. Regardless, they emphasize the importance of convincing the decision-maker of the credibility of the model for decision-making purposes. Care must be taken when using past performance. Pritsker (1986) warns that past performance may only represent one sample and not necessarily the exact answer. Dalkey (1968) agrees and adds that even if the two disagree, the model may still be valid. He points out that chance, model detail and a commander's decisions all affect historical outcomes. He emphasizes that a major factor in war is a commander's

decisions and presently there is no adequate way to model these decisions.

Lee, Moore and Taylor (1990) warn that simulation modeling is particularly susceptible to the garbage in-garbage out syndrome. Pritsker (1986) sees the validation process as a way of answering two questions. They are:

1) What is the inherent variability within the model?

2) What can be inferred about the real system performance from the model performance?

He claims the first question deals with understanding the model and assuring the model operates as intended. The second deals with the model's usefulness. The first involves obtaining a detailed statistical analysis on the precision and sensitivity of the model. The second question is related to the modeled system and, therefore, model dependent, and as such there are no general analysis methods that can be recommended beyond the standard statistical tools.

Khoshnevis (1994) states that there are two different approaches to model validity. Empiricism and Rationalism. Pegden (1990) adds a third he calls Positive Economics. Rationalism is an approach that assumes most of the underlying assumptions a model is based on are obviously true and therefore in no need of proof. Logical deductions are then used to develop the model and, as such, if the assumptions and logic are valid, then the model is valid. The empirical approach demands that every assumption and

result be empirically tested and validated. No assumption is allowed that cannot be independently tested or verified. The Positive Economics approach only requires that the model be capable of predicting the future. It is not concerned with validating the underlying model assumptions or structure. Thus, if the model has good predictive capability, it is assumed to be valid. Although Law and Kelton (1991) and Khoshnevis (1994) both provided several approaches to increasing model validity, Pegden (1990) provided the most complete list. He broke these approaches into three areas. They include tests for reasonableness, tests of model structure and data, and tests of model behavior. Within tests for reasonableness, he recommends checking the following:

Continuity: Small changes in the input data should result in small but appropriate changes in the decision variables.

Consistency: Similar runs of the model should result in similar outcomes.

Degeneracy: If model features are removed, the decision variables should reflect their removal.

Absurd Conditions: This has two parts. (1) If the modeler provides unusual data input, the model should not give unusual or unpredictable results. (2) The model should never generate absurd or impossible situations.

For testing the model structure and data, Pegden (1990) proposes these tests:

Face validity: This is accomplished by asking experts of the modeled system whether the model's behavior seems reasonable.

Parameters and Relationships: This area includes tests of assumptions concerning parameter values and variable relationships and typically involves statistical tests such as means, variances, regression analysis, and goodness of fit tests.

Structural and Boundary Verification: The key here is to ensure that the structure of the model does not clearly contradict the real system.

Sensitivity Analysis: This is done by varying the model input parameters and checking the impact of these changes to the model's outputs. This should give us some idea how sensitive the model is to small changes in the input parameters.

Also, he suggests a number of tests for investigating model behavior:

Behavior Comparison: This involves comparing the model output to the real system results. He lists a number of statistical tests that are available including the Chi-Square test, Kolmgorov-Smirnov test, and regression analysis.

Symptom Generation: These tests take different forms but answer questions like:

- Can the model produce the same difficulties that show up in the real world?

- Does it produce the same results after a change as the real system did after similar changes?

Behavior Anomaly: If the model gives results that conflict with the modeler's expectations, can the modeler find examples of this behavior in the actual system. If he cannot, there may be a problem with the model.

Behavior Prediction: Use the model to predict system performance during field tests by controlling inputs to both the model and the actual system.

Finally, Law and Kelton (1991), Shannon (1975), and Pegden (1990) stress that verification and validation are ongoing tasks and should not be left until the end of the project, to be done if time and money permit. Figure 1 illustrates the continuous roles verification and validation play in the model development process. This section concludes with a thought by Shannon (1975):

> The question of validation is thus two-faced: determining that the model behaves in the same fashion as the real system; validating that inferences drawn from the experiments with the model are valid or correct. In concept, both these points resolve themselves to the standard decision problem of balancing the cost of each action against the value of

the increased information and the consequences of erroneous conclusions.

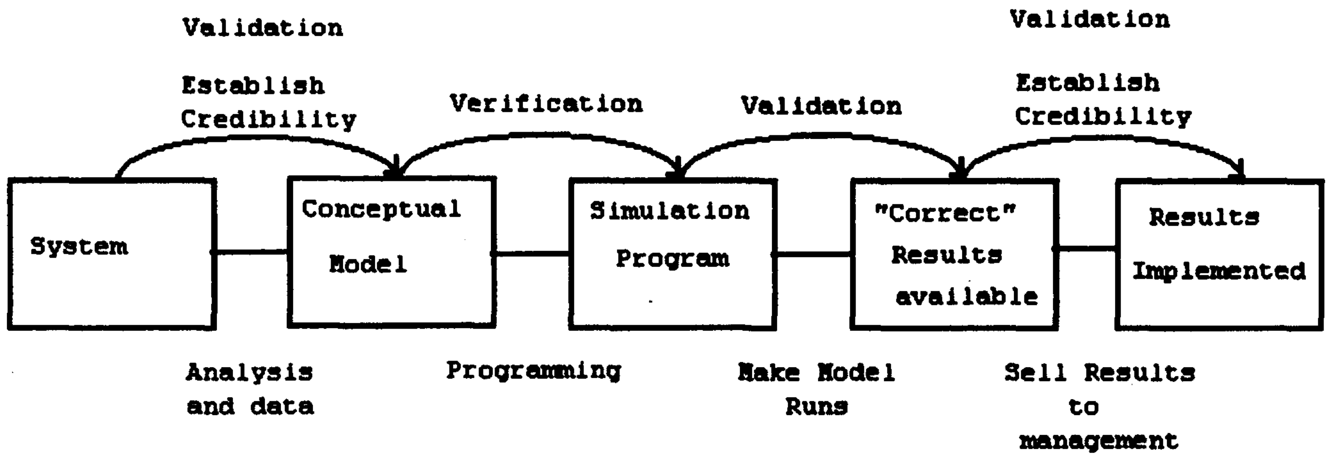

Figure 1. The Continuous Nature of Verification and Validation (Adapted from Law and Kelton, (1991))

Chapter III: METHODOLOGY

The research can be broken into three general parts. These areas include data gathering, model development and validation, and a model output analysis plan. The research will identify current shortcomings of the current Air Force combat aircraft assessment techniques which center around the use of the Dyna-METRIC model. Then it will consider several analytic and simulation-based techniques to determine a better method. My approach in each area will be discussed below.

Data gathering or more accurately information gathering will occur in several ways. Aircraft demand and repair information will generally come from HQ ACC/LGSW although HQ AFMC is a secondary source. Part of this research will consider what data elements are actually necessary for these assessments. Current information on the model capabilities comes from a wide variety of sources. In addition to the two sources listed above, I expect to receive information on the model from HQ AF/LEYS, Logistics Management Institute (LMI), Dynamics Research Corporation (DRC) and RAND Corporation. Each of these groups has an active interest and involvement in the current model and future assessment developments. Military regulations and manuals will also provide guidance. Finally, current literature provides an additional source of information on the current assessment

method and knowledge about other techniques which could be adapted or developed into a method for addressing this problem. Various models for comparison with the research model will come from RAND, DRC, or HQ ACC/LGSW. The data gathering efforts should feed the methodology development and data analysis section of this work.

Methodology development and validation represent the heart of this research project. This involves a number of steps. A clear understanding, explanation, and demonstration of the problems and shortfalls of the current assessment methodology must be established. This can be done through a thorough literature review and discussions with the practitioners in the field. Based on this process understanding, other possible methods and modeling techniques can be investigated as improvements to the current process.

Several approaches appear promising as starting points for this research. The first is based on Jacksonian networks (Jackson, 1957 and Jackson, 1963). Gross et al. (1983) used this networking method to develop a technique to optimize sparing levels and repair channels. It is an extension of earlier work done by Mirasol (1964). Mirasol built a model which considered a single-echelon, single-repair shop, infinite calling population, finite repair capacity system. Gross added to this work by considering a finite population of operating times and a two echelon repair system. The drawbacks with this method are that it

only considers steady state conditions and it was built to optimize sparing levels based on cost not to determine availability based on sparing levels. Another promising approach uses a method developed by Sherbrooke (1992) for the NASA space station Freedom. It is conceptually similar in many ways to the METRIC-type models but does not use Palm's theorem because it does not assume that the shapes of the repair distributions are unimportant. It also does not use an infinite population assumption to distribute backorders. One drawback of this method is that it still assumes an infinite calling population for demands. Kaplan(1989), however, developed a model similar to Isaacson (1988) but includes the finite calling population assumption in his model. This technique could be adapted into Sherbrooke's model (1992) or possibly extended as a primary method.

When a technique has been selected, it will be developed and validated. Model validation, defined as raising the decision-maker's confidence to an acceptable level, will include a number of steps (Shannon, 1975). Checking the face or structure and assumptions validity of the method and checking an input-output transformation analysis with the current method and with a real deployment are two of the steps. The structure and assumptions testing will be an iterative process involving the field experts. As developments are made, they will be checked with the agencies mentioned earlier for credibility and accuracy.

When these groups are satisfied that the method is structurally sound, this portion of the validation will be complete. Once the method has been developed and the structure validated, it can be compared with the current method and reality. The data analysis section deals with this part of the research. The users will provide the expert input for face-value and output validity tests.

The data analysis plan depends on the new assessment method selected and results from the current method and a live aircraft test. The current method uses number of sorties flown during the deployment period and the number of combat ready aircraft available at the end of the deployment period as the measures of merit. Since these are the Air Force standard measures, this study will also use them as the basis of method comparison. HQ ACC plans an actual deployment test of B-1 aircraft to Roswell, NM in November 1994. The data collected from this test will form the basis of the live data set. To ensure a reliable comparison between this actual data, the current method, and the new method, the two modeling methods will use the same scenario and assumptions that are being used during the B-1 test. Using this input data, the two models will be run and their output collected. Based on the output from all three sources, a series of two-sided Hypothesis tests will be created to test the differences between the data sets. The null hypothesis will be that there is no difference between the data sets while the alternative hypothesis will be that

there is a statistically significant difference in the data. These hypotheses will be tested at a 95% significance level. As a result of these tests, a discussion of similarities and differences between the data will be made. Also, conclusions and recommendations for future work and possible implementation of this method in the Air Force will be made.

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